European Challenges and Flagships 2020 and beyond

Report of the ICT Advisory Group (ISTAG)

July 2009

SEVENTH FRAMEWORK PROGRAMME

European Commission
Information Society and Media

The Publications Office of the European Union.

ISBN 978-92-79-13879-9
doi 10.2759/23475

Terms of Reference

Task of the ISTAG FET Working Group regarding the flagship initiatives

- The ISTAG FET Working Group should focus on defining the FET flagship initiatives to address ICT-relevant scientific and technological challenges, and present a few (3 - 5) candidates for such initiatives.
- Part of the reflection to determine these initiatives could be Europe's future socio-economic challenges but we need to keep in mind that FET activities are not only driven by socio-economic considerations. Progress of ICT science and technology beyond current frontiers is an important driver of FET.
- This is why the FET flagships should be ambitious, large-scale science-driven and goal-oriented initiatives aiming at unprecedented scientific discoveries and technological innovation that require essential transdisciplinary research and a federated effort by the EU, member states, and if appropriate, global partners.

Foreword

The European Commission formed the ICT Advisory Group (ISTAG) to provide advice to the Commission services regarding the ICT Theme of the Cooperation Specific Programme, part of the 7th Framework Programme for Research and Technological Development. As part of the ISTAG, a working group on Future and Emerging Technologies (FET) has been established with a two year mandate to provide strategic advice and orientations on long term foundational research, in order to strengthen and broaden the science and technology basis of future ICTs.

On the basis of a previous report (First Report of the ISTAG on FET) elaborated by the working group, the ISTAG chairman asked the ISTAG FET WG to perform an analysis of the scientific and technological areas where European research is strong, to determine the main scientific and technological challenges for 2020 and to propose flagship initiatives. FET flagships should be ambitious, large-scale science-driven and goal-oriented initiatives aiming at unprecedented scientific discoveries and technological innovation that require essential transdisciplinary research and a federated effort by the EU, member states, and if appropriate, global partners. This has culminated in the present report which elaborates on this concept and illustrates it with preliminary descriptions of topics for potential FET flagships in Research and Innovation (FET-F) for 2020 and beyond. These FET-F examples are defined in scientific and technological areas where European foundational research is strong and where we believe that they will have a strong societal impact and evolve future markets in which Europe should play a prominent role.

There exist many reports attempting to propose ICT Grand Challenges. We underline the quality of the reports « Grand Challenges in the Evolution of the Information Society » written in 2004 by the ISTAG, « Beyond the Horizon: Anticipating Future and Emerging Information Society Technologies » written by ERCIM in 2006 and the COST Foresight 2030 report of 2008. Most of the foreseen challenges are still very timely. However their focus is restricted either on technological challenges or on research challenges. We do believe that the present report goes one step further by providing flagship initiatives based on European expertise to address the envisioned challenges.

This report marks the first steps in identifying promising topics and criteria for FET flagship candidates with the ultimate goal of launching such flagships as outlined in the Communication "Moving the ICT frontiers – a strategy for research on future and emerging technologies in Europe" which was adopted by the European Commission in April 2009. In this communication it is highlighted that the Commission will collaborate with Member States and the research community to identify and define potential FET flagship initiatives and launch at least two by 2013.

The chairmen sincerely thank all the members of the working group for their efforts and individual contributions, which were performed with complete independence and total scientific freedom. Special thanks to Pouline Middleton and Magnus Madfors for joining the working group. Discussions and debates were open, vigorous and sometimes colorful, but they always succeeded in consensual advice and recommendations. In addition, we gratefully acknowledge the considerable support of the officers of the FET Units.

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Executive Summary

This report is the contribution of the FET working group of the Information Society Technologies Advisory Group (ISTAG) to the definition of FET flagships (FET-F) that address challenges in research and innovation requiring radical transformations of ICT for 2020 and beyond.

A FET flagship is defined in a scientific and technological area where foundational research is strong in Europe, in the sense that essential competences and a range of dispersed initiatives exist that are mature to be brought together in order to achieve the next level of ambition. This will have a strong societal impact and evolve future markets in which Europe should play a prominent role. FET-Fs will present novel and ambitious goal-driven initiatives for developing and keeping this leadership and for transforming it into a significant competitive advantage for Europe. FET-Fs aim at unprecedented scientific discoveries and technological innovation from essential transdisciplinary research. It can only be achieved by a joint effort of the EU, its member states, and where appropriate, by including industry and international partners. Since the ambition is huge, a FET-F should be based on outstanding researchers and innovators, including world-wide partnerships.

Existing funding mechanisms may serve as building blocks in a cluster-based FET-F approach. Joint programming and alignment with national priorities are essential on an opt-in basis. To accomplish its scale of ambition, a single FET-F requires a strong support for at least 10 years. The required level of funding will be defined per flagship and is expected to be typically at least one hundred million Euros per flagship per year. It will be accomplished by combining existing and new European and national resources for creating critical mass and achieving integration and by leveraging additional resources from the EU, national governments and industry.

The structure of society and the role of the state will undergo major changes towards 2020 and beyond in order to build the future sustainable society. It is widely recognized that ICT is a major enabler for these changes. However, incremental innovation is not enough, radical innovation is necessary. The emergence of new markets has to be deeply intertwined with the development of radically new innovations based on interdisciplinary and solution-oriented approaches. The role of the state (for example precommercial public procurements, creation of economic incentives), the role of the market (going from the single market concept to a more contextualized and individualized value model) and the role of public infrastructures have to be evaluated with respect to future challenges. And the capacity to cooperate among sectors, break the barriers, and create new markets has to be radically developed.

Research quality and capacity are excellent in Europe. However, it is mostly driven at national level (member states) which results in fragmentation of competing initiatives. Competition is essential in research but it should be at a world wide scale and more coordination at the European scale is crucial in order to obtain critical mass, define strategic priorities, launch ambitious research-based and goal-driven initiatives, speed-up the take-up of results and enable scale of economy for industry.

This report defines the criteria to use when identifying European FET-Fs. Eight criteria have been selected and defined: **Goal, Impact, Novelty, Ambition, Interdisciplinary research, Resources, Plausibility and Sustainability.**

Finally the report proposes five candidate topics for European Challenges and flagships in Research and Innovation and motivates the selection. They will be later assessed against the eight criteria defined in the previous section. These candidate flagship topics are the following:

- **Understanding Life through future ICT**
- **Anticipation by simulation – Managing complex systems with future ICT**
- **Future Information Processing Technologies**
- **The team player - Future Problem Solving Technologies**
- **Robot Companions for Citizens**

Obviously a closer analysis has still to be done, the selection of the flagships has to be confronted to experts of the fields and the SWOT analysis has to be performed in order to assess the importance and respective merits of each of these FET-F candidates.

1 Introduction

This report is the contribution of the FET working group of the Information Society Technologies Advisory Group (ISTAG) to the definition of European flagships (FET-F) that address challenges in research and innovation requiring radical transformations of ICT for 2020 and beyond. This report clarifies this idea and identifies a set of candidate topics for such initiatives.

A FET flagship is defined in a scientific and technological area where foundational research is strong in Europe, in the sense that essential competences and a range of dispersed initiatives exist that are mature to be brought together in order to achieve the next level of ambition. This, we believe, will have a strong societal impact and evolve future markets in which Europe should play a prominent role. FET-Fs will present novel and ambitious goal-driven initiatives for developing and keeping this leadership and for transforming it into a significant competitive advantage for Europe. These initiatives constitute a structural advantage for Europe by providing new opportunities for a sustained research effort in the direction of a common long-term vision.

FET-Fs are ambitious, large-scale, science-driven and goal-oriented initiatives. They aim at unprecedented scientific discoveries and technological innovation from essential transdisciplinary research. Their ambition is of such a high level that it can only be achieved by a joint effort of the EU, its member states, and where appropriate, by including industry and international partners. FET-Fs will create or maximize a leveraging effect, and promote continuity of support (beyond the lifetime of individual projects).

FET-Fs concretize European visions of the future. They consist of forefront projects that collectively represent a large focused and coordinated effort towards a major goal that no single EU country, or small group of EU countries on their own could achieve. A FET-F builds on existing instruments such as Networks of excellence, STREPs, IPs, ERC-grants, which it uses as building blocks, and complements other initiatives such as ETPs and JTIs. They constitute a new, additional contribution to the European Research Area.

Since the ambition is huge, a FET-F should be based on outstanding researchers and innovators, including world-wide partnerships. It is an EU-centered international project. Hence the initiatives should rely on a network of outstanding people but be different from networks of excellence in being more purpose driven and with integration in terms of content, not necessarily in terms of research infrastructure. Existing funding mechanisms may serve as building blocks in a cluster-based FET-F approach. Joint programming and alignment with national priorities are essential on an opt-in basis. EIT KICs, especially in ICT but not only, may be involved in FET-F since they share the same goal of improving EU transnational coordination, enhancing the scale of impact and growing the critical mass in order to reduce fragmentation and boost research quality in EU.

To accomplish its scale of ambition, a single FET-F requires a strong support for at least 10 years. The required level of funding will be defined per flagship and is expected to be typically at least one hundred million Euros per flagship per year. It will be accomplished by combining existing and new European and national resources for creating critical mass and achieving integration and by leveraging additional resources from the EU, national governments and industry.

2 Radical innovation from interdisciplinary research creating new markets

The structure of society and the role of the state will undergo major changes towards 2020 and beyond in order to build the future sustainable society. It is widely recognized that ICT is a major enabler for these changes. If we consider as an example the market dynamics generated in online marketplaces and the related sophisticated financial tools, ICT has opened up new possibilities that businesses and citizens can pick up and exploit. However applying ICT to societal needs is not a neutral act: the previous example shows that the consequences can lead to exponential creation of wealth or to unprecedented worldwide economic crisis.

However, incremental innovation is not enough, radical innovation is necessary. Markets are conservative in their basic nature and therefore ill-equipped to adopt radical new approaches. New ideas, business models and technologies are only picked up by the market once the insecurities around them have been lifted and cleared. The emergence of new markets has to be deeply intertwined with the development of radically new innovations.

The capacity to define and cater to people's and society's needs is another crucial parameter. Hence interdisciplinary and solution-oriented approaches are necessary. The role of the state (for example precommercial public procurements, creation of economic incentives), the role of the market (going from the single market concept to a more contextualized and individualized value model) and the role of public infrastructures have to be evaluated with respect to future challenges. And the capacity to cooperate among sectors, break the barriers, and create new markets has to be radically developed. Previous attempts (living labs for example) to solve this problem have not been fully successful.

Research quality and capacity are excellent in Europe. However, it is mostly driven at national level (member states) which results in fragmentation of competing initiatives. Competition is essential in research but it should be at a world wide scale and more coordination at the European scale is crucial in order to obtain critical mass, define strategic priorities, launch ambitious research-based and goal-driven initiatives, speed-up the take-up of results and enable scale of economy for industry.

These methodological challenges will be addressed by setting up a number of large scale interdisciplinary FET-Fs.

3 Criteria for European future FET-F's

This section defines the criteria to use when identifying European FET-Fs. For each research and innovation area, a SWOT analysis has to be performed in order to further underline and motivate usage.

Criterion 1 Goal: Is the goal a major challenge for science, society and industry in the 21st Century? Is the goal focused with a unified purpose? Is achieving the goal essential for Europe to be a major competitor in the area of the proposed research?

Criterion 2 Impact: What can it lead to and when? What are foreseen consequences, opportunities and repercussions in terms of societal impact, impact on science and technology, innovation and the creation of emerging markets?

Criterion 3 Novelty: A FET-F is a new and visionary European ICT initiative that concretises a European vision of a sustainable future society. Are there competing initiatives or is the FET-F project unique? Are there ongoing initiatives to build on and how does their federation allow addressing a novel goal that can not otherwise be achieved?

Criterion 4 Ambition: Does the FET-F address a major challenge in the 21st century? Does it require a large unified and international effort towards a single goal? What makes the project to be far beyond any thing that exists today? Is it a big and essential leap forward in the area of research proposed?

Criterion 5 Interdisciplinary research: What disciplines are required to achieve the goal of the FET-F? What methodological approach is used to bring all these disciplines together? Are other disciplines required? Who is driving the proposal? What synergistic strengths do the partners bring to the project?

Criterion 6 Resources: What resources are available? What is the significance of the building blocks and initiatives that this builds on? Does the project have a strong center of operations? What are the main contributions of the partners in the project? What leveraging effect could it create in institutes, governments and industry?

Criterion 7 Plausibility: Is there a well-defined roadmap that makes attainment of the eventual goal plausible? Have the component areas of research reached critical mass in its proofs of concepts to justify a leap in resources and an international effort? Are the milestones reasonable? How achievable is the goal with the proposed amount of effort?

Criterion 8 Sustainability: Does the project improve on the sustainable use of resources? Does it include concrete measuring points in terms of sustainability issues related to the activities performed? Does it include a plan of how to improve on the measuring points within the duration of the flagship project?

4 Candidate FET-F's

In this section, we propose five potential topics for candidate European Challenges and flagships in Research and Innovation. They will be later assessed against the eight criteria defined in the previous section. We first try to motivate our selection.

Schematically the major societal goal is to live longer in better health, in a secure environment and with prosperous conditions. Although we do not pretend that it could solve alone this problem, we do think that ICT may have a crucial impact on making progress towards this goal.

With respect to health, impressive progress has been made in the last 50 years. However a lot has still to be done, but may be impossible without a breakthrough in life sciences. Such a breakthrough, which we call "Understanding life", is no longer science fiction but is becoming a feasible challenge thanks to the advances in biological sciences and in ICT.

Providing a sustainable environment to society is becoming the most urgent task. The solution of this problem is certainly complex and will need all kinds of expertise. However the contribution of the sciences may be multiplied by an unprecedented change in the way they are performed. ICT has made possible a radical evolution toward simulation-based research. Accurate models of complex systems on a global scale, even those where no real experiments are possible, are in prospect. Simulation based solutions may be provided and evaluated for predicting trends, evolutions, catastrophes, for building tools for sustainable production and consumption and for achieving an effective and reliable economy.

Citizens need to be assured of the security of the complex systems that they do not control and on which they depend. The information society is becoming more fragile with respect to the threats of a totally networked world. The evolution of the internet and of software production has to address this challenge with radically new methods.

These societal challenges cannot be addressed from the point of view of ICT alone; neither can this be done by incremental progress only, as we have seen. This is even more true for ICT itself, in particular for what concerns the physical limitations of the computing technologies. Breakthroughs in quantum computing, in bio-computing and towards 0-power computing, to name just a few, are necessary.

Robotics technology holds great potential to improve societal welfare by addressing such critical issues as health, ageing, safety, security, environmental protection. Intelligent and cognitive robots with adaptive, learning and evolutionary capabilities that can perceive, understand and interact with their environment are needed to achieve these goals. They may be the ultimate step of the integration of the most advanced ICT technologies. They not only serve as a challenge for research but at the same time provide a laboratory for testing new technologies, and ultimately will provide services to improve the quality of life of human beings.

A description of the content and objectives of each candidate flagship is presented in the following sections. We are aware that the depth of each description and their balance is based on the expertise available in the working group.

4.1 Understanding Life through future ICT

Life science is being driven by an explosive increase in the technological capability of researchers and bioservices industries to probe living organisms and extract vast amounts of data on their composition, functions and dysfunction across all levels of biological organization. This growing data deluge is transforming the very method of science as researchers can spend more time exploring fundamental and emergent principles of biological organization than on data gathering. The biological and biomedical sectors are also being revolutionized by the availability of multi-facetted data ("multi-omics") obtained from patients, which are driving a rapid increase in the number of clinical data repositories and an exciting new opportunity of informatics-based medicine. Medicine is bracing itself for an even larger deluge of genomic data within the next few years that will demand massive multivariate correlation analyses as we enter the age of genomic predictors of life and its diseases. Modeling genes, proteins, cells and organs is also rapidly moving from high-level theoretical abstractions of living processes to bottom up models based on vast amounts of biological data and first principles that are moving towards a process of "capturing biology" in software and hardware. The theoretical abstraction of biology into accurate models is involving the disciplines of mathematics, physics and chemistry in a deeper way than ever imagined, while data gathering, simulation, and visualization are involving all facets of computer science and engineering, software engineering, and the full spectrum of information technologies. ICT has therefore become an integral part of the process of understanding life and its diseases. ICT is not only enabling these revolutions in the life sciences, but the rapid advances in probing life is also demanding and driving new computing capabilities, novel algorithms, a vast range of software products, internet technologies as well as novel ways to manage peta to exa to zeta scale data volumes. Understanding biological intelligence also has the potential for development of novel biologically inspired hardware and software architectures as well as robotics to go beyond von Newman type computations to more analog, molecular and quantum computations. The capabilities of all these disciplines to work together to probe and capture the inner secretes of life as well as the emergence of new technologies that are becoming capable of moving beyond understanding life to designing life, are also posing major ethical challenges in the 21st century. FET flagship projects centered on understanding life should therefore prepare the EU in all ways for a new generation of science, medicine, technology, ICT and society.

Screening Life Challenge: A data and informatics center to gather and organize data across all of life's organisms and across all levels (genes to behavior, normal variations, diseased variations). This requires industrial-scale screening facilities across multiple levels of biological organization, exascale storage, self-managed data facility and novel software platforms. It builds on research efforts on synthetic living ICT, evolutionary technologies, synthetic biology, bio-ICT, among others, and builds up EU's data-assets and foundations for correlation-based predictions.

Simulating Life Challenge: Simulation based research facility for the life sciences for simulation-enabled research based on first principles and accurate experimental data. This requires the most advanced and new types of supercomputers, exabyte storage facilities, high-end on-site and remote visualization facilities, and novel software architectures and products. This revolves around screened life data assets and builds up EU's predictive, design and diagnostic capability.

Emulating Life Challenge: High-end bio-inspired robotics to enhance technologies. It requires a central engineering facility, simulation-based research, capturing biological intelligence. This gathers research efforts on Living robots, Embodied and Soft-bodied ICT, among others, and builds up EUs future technological capabilities, as well as driving zero energy targets.

Neuro-ICT Challenge: Neuro-ICT is required to more effectively manage and direct technologies of the future and foster EU's capability to effectively and efficiently interface and manage with emerging technologies of the 21st century. The research includes screening life data assets, simulating life capabilities, emulating life, know-how and technologies, from photonics and imaging as well as nano- and micro-engineering. This builds on neuroinformatics, brain-computer interfaces, hybrid bionic systems, visual computing, creativity, and micro-scale hybrids.

Personalized ICT for Health Challenge: Personalized dynamic linking to health and disease data and diagnostic centres to provide real-time, anywhere, and self-managed healthcare. It requires on- and in-body technologies, screening life data assets, simulation-based research, and ICT technologies for emulating life. This builds up EU's capability to cope with growing healthcare needs and enhancing individual healthcare independence and well-being.

Personalized ICT for Education Challenge: Personalized ICT systems for guided education, cyber tutoring, and virtual universities. It requires dynamic real-time, anywhere technologies to link to educational and data resources to deliver personalized data, knowledge, guidance, tutoring. This builds up EU's capability for unlimited, unrestricted, facilitated and personalized education across at any age.

Personalized ICT for Wellbeing Challenge: Personalized ICT systems for social interactions, entertainment and general well-being. It requires real-time anywhere technologies to link to social, educational, entertainment, mental health and other assistive resources to maintain health and social wellbeing as life span increases. This builds up EU's preparedness for dealing with complications of longevity.

4.2 Anticipation by simulation – Managing complex systems with future ICT

Research of recent years has opened new dimensions of understanding and predicting the world around us: the decoding of the Human Genome, the design of new materials according to required properties, the detailed warning for catastrophes to name a few. These topics have in common, that they address complex systems in nature, in business or on human level. These results became possible, because of the enormous improvements in price and performance in computer technology, in software complexity, as well as in new algorithms and computing paradigms over the past two decades and they will continue over the years to come. Another key advance is the possibility "reality-mining", which has been defined as the collection of machine-sensed environmental data that are related to human social behaviour. These advances allow the gathering of large data set on the social component of complex systems, a dimension that is crucial in the analysis of most complex systems. The key competence for understanding and managing complex systems lays in the data driven modeling, simulation and optimization, often also integrated in decision support systems. The above named research results were typically big one-time efforts. On a broader base, a mainstream competence in solving similar complex system challenges on a further advanced technology level will provide dramatic changes and improvements for many aspects of society, business and for the individual.

Data driven simulation is an essential analysis and prediction technology for the solution of nearly all real-world problems regardless of existing, virtual or conceptual complex systems: understanding of system's behavior, evaluation of specific properties, decision support, training, planning scenarios and what-if-questions. Simulation is strongly connected with the modeling technology that describes the functionality, structure and behavior of the considered system. Both technologies require strong interdisciplinary collaboration to transmit the power of ICT to the domain of the respective challenge. Typically, these methods address the most complex and difficult problems and provide deep insight into the mechanisms and dependencies. Moreover they provide a firm basis for improvements up to full optimization. Thus modeling, simulation & optimization (MSO) form the key technology cluster.

Europe has a strong position in these areas and their applications, providing an excellent basis to build scientific and technological leadership in mastering complex systems. As the key method is ICT based, it can be adopted to many different challenges. The following examples show the potential power of this research theme in a selection of examples:

Predicting trends, evolutions, crisis: *Improved prediction of the future*: understanding trends and evolutions, their dynamics and their future impact both qualitatively and quantitatively. Allows assessment of actions and decisions. In case of *catastrophes* it allows for better preparation and limitation of damage. Provides insight and recommendations for preventive and counter measures. Identification and assessment of *impact of disruptive events*, like economic crises, changes in prices (like oil or food) but also impact of business models. This requires sophisticated MSO technologies e.g. learning from data, forecast technologies based on learning systems etc.

Achieving an effective and reliable digital economy/service-based society: The *restructuring of our society* that is required to achieve a sustainable future will fundamentally change the way in which citizens, private sector and public sector interact. The borderlines between society, state, business and citizen are becoming virtual. For an increasing number of jobs or other interactions, physical presence will not be required or even be discouraged and replaced by ICT supported interactions (the term home-sourcing is started to be used for this way of working). The transformation from traditional (closed) businesses towards open business structures will require next generation ICT applications transforming from factory-worker workflow systems to knowledge worker decision support systems (we already see traditional vertically integrated businesses dissolving into ecosystems of more specialized suppliers, heavily driven by integrated supply chain ICT systems: outsourcing, off-shoring, contract manufacturing). This transformation towards decision support will heavily depend on MSO.

Intelligent energy awareness within sustainable production and consumption: Optimized use of *energy in industrial systems*, like production (eco-efficient plants and products) and logistics and even avoidance (virtual factory, virtual products both in the design phase). Design of optimal global intermodal solutions for routing and door-to-door solutions, thus providing the basis for significant reduction in energy consumption and corresponding climate impact of industrial processes and transportation.

Sustainable infrastructures and traffic management: Construction of eco-friendly infrastructures (for example water, wastewater, district heating) requires advanced simulation techniques, such as for simulation-based support systems for intelligent operations, optimized traffic flow in cities and at bottlenecks and interfaces, reliability in complex logistics, and control and management of crowds.

Technology and engineering: Future solutions will provide all kinds of applications arising using augmented and mixed reality covering a wide spectrum from surgery to manufacturing to social networks or computational fluid dynamics. Modeling and simulation will fundamentally change the engineering tasks of these endeavors: Robust design enabled by automation and simulation will significantly reduce time, risks and faults in product, systems and process development, a traditional strength of European industry.

An overview of critical challenges for future modeling and simulation starts with mathematical-algorithmic expertise and further comprises context and knowledge modeling, machine learning, decision support by planning and forecast technologies. Modeling and simulation for large-scale systems comprise various technologies like multiscale, multilevel and multiphysics simulation, hybrid modeling, automated model generation and transformation, eco-system computation, large-scale simulation, overlay computing and communication, wire to service, pervasive adaptation. Options to focus research comprise the following directions:

Holistic modeling & simulation competence: Today's modeling and simulation frequently build upon the effects of reducing the models to lower dimensionality. This strongly reduces the ability for detailed understanding and optimization options, on the other hand it often allows to identify surprisingly good solutions, however for a few selected requirements only. Therefore new methods must be investigated to design holistic models of target objects. These methods must be able to describe the model in an adequate dimensionality. As this may be quite abstract and complex, an automatic model building must be addressed.

Interoperability & Simulation Architectures: Simulation model development is labor and cost intensive. Modularization, i.e. the formation of reusable simulation components, can be a solution. On the one hand neutral model formats are necessary to exchange models between different companies (e.g. in a supply chain) and on the other hand interoperability is required to achieve plug&simulate capabilities. On the application level a common simulation architecture concept is needed to execute different simulations in cooperation with human machine interfaces (HMI), data bases and other software and hardware systems. This includes data exchange mechanisms and communication protocols.

Concepts for autonomous systems modeling: Research in this area could also be directed to autonomous systems that perceive the environment, understand the situation, draw conclusions, act in an appropriate manner and cooperate with other systems. These systems may differentiate from the others in this discussion, as they would not preliminarily simulate an existing topic, but address new challenges arising, for example from process management needs.

Modeling & simulation based upon non-von Neumann principles: Modeling and simulation base very much on the methods of the digital computer, linear structures and parallel data management. This provides a variety of solutions to adequate challenges, but is generally hampered by the fact that the world is analogue, non-linear and shows lots of dependencies. The solutions implied are therefore strongly shaped by current computer architecture. To address this effect research should address several issues:

- build teams, who are not "digitized" in their thinking patterns
- work in interdisciplinary teams with participants with no-IT background
- drive model & simulation descriptions in "natural" language
- In a more technology oriented program this topic requires a clear orientation to non-von Neumann architectures. Options include:
- biological computing architectures
- quantum computing architectures.

We emphasize the strong connection existing between modeling and simulation based on non-Von Neumann principles and novel information processing devices. Indeed, as technology is making it possible to surpass the Von Neumann architecture, advances in converting achievements of theoretical modeling and simulation into practical, workable structures require proper attention.

4.3 Future Information Processing Technologies

Future information processing technologies include computing technologies, novel devices, sensing and actuation, interacting and communicating technologies.

Quantum information processing represents a shift of paradigm for information technologies: Some of the most far-reaching applications of quantum mechanics — such as the transistor and the laser — represent the building blocks of current electronics and telecommunications, and have heralded the birth of information society as we know it today. Yet, they merely act as a support for a completely classical mode of processing information, where logical degrees of freedom exhibit no quantum behavior whatsoever. Quantum Information Processing and Communication (QIPC) has explored the use of quantum-physical systems to perform calculations of complexity unattainable by systems behaving classically. Through the combination of quantum physics with information science, it has created in the past ten years new and unprecedented means for communicating and computing. By harnessing and putting to work in cutting-edge experiments counterintuitive concepts such as quantum superposition and quantum entanglement, it has lead to novel, practical and useful applications.

As many branches of QIPC have gone past the proof-of-principle phase, the further advancement of the field towards industrial dissemination and commercial exploitation implies integration of the scientific base built, to conceive technological applications of quantum coherence and entanglement.

The proposed FET-F in Quantum Information Technologies (QIT) will therefore take care of bringing this strategic field one step closer to its industrial dissemination and commercial exploitation. The possibility offered by these technologies is extremely vast, ranging from metrology, imaging, security, telecommunications, etc. Quantum technologies should be developing in two complementary directions.

Future quantum devices: The first challenge to establish quantum technologies is to develop reliable truly quantum devices. They are presently at an early pre-application stage, but possess a novelty and a richness that suggests an equal or even greater impact than the one of the transistor and the laser. These include on the one hand single- and entangled-photon sources and detectors for quantum communications, and on the other hand single atom or ion traps or chips as quantum gates, which will be the building blocks for quantum computing. Solid state quantum device are at an even earlier stage and include quantum manipulation of ions in crystals or electrons in semiconductors aiming to exploit properties such as spintronics.

Quantum information processing and quantum computing: New quantum communication protocols will guarantee the absolute security, proven from basic principles, of all kinds of commercial transactions including the ones performed through the future (quantum) internet. This field is the most advanced one in quantum technology and has already been commercialized.

Quantum metrology and sensors can be used to overcome the classical limits in various kinds of measurements. Entanglement of atoms in clocks are expected to improve state-of-the-art atomic clocks. Nanometer sized rods and cantilevers should become sensors for the detection of extremely small forces and displacements. Quantum imaging should provide an increase of the optical sensitivity beyond the wavelength limit with applications in pattern recognition, image segmentation, optical data storage.

Quantum computing, relying on principles different from classical computing, should allow unprecedented computing power with which the understanding of complex systems and phenomena will become feasible. Quantum simulators should provide answers to problems which are fundamentally beyond classical computing capacities, such as the study of microscopic properties of materials, the accurate description of chemical compounds and reactions, the design of fundamentally new drugs.

Concrete options to focus a research agenda on such novel information processing devices include:

Switching devices: As silicon CMOS technology scales down towards ultimate dimensions, new device structures will be required to replace and augment standard CMOS devices for ULSI circuits. With device dimensions well into the nanometer scale, concerns such as complexity, variability and reliability are increasingly coming to the foreground. Moreover, as the on-chip density of devices increases, their power dissipation must decrease, leading to the limiting concept of zero-power electronics. And all this needs to be done in a cost-effective manner, so that the density advantages of nanoscale circuitry are not compromised.

The emerging nanodevice technologies span the realm from nanowire transistors over spin-state switches to devices made from bottom-up assemblies of molecules. Most of those devices will require significant breakthroughs in the development of nanomaterials and the associated fabrication processes. However, control of molecular properties in a solid-state circuit environment is still at a very early stage. There is therefore a strong need for both fundamental and applied research in conceiving and implementing novel high-performance, enhanced-functionality atomic or molecular integrated devices, modules and platforms, and high-yield bottom-up fabrication technologies. There is also a need to adapt current logic & memory architectures to the specificities of molecular switching and the requirements of terascale integration based on these devices.

The unique characteristics of nanoelectronics will allow novel circuit architectures, based on heterogeneous integration of hybrid circuit components. This process is already well under way in the More than Moore trend, linking processor and memory circuits with different kinds of sensors and actuators on a common substrate. However, there is a need for much more systematic approaches in terms of design architectures and systems partitioning for complex heterogeneous systems, also taking into account a broad variety of process technology challenges when including ULSI approaches into design methods. There is a huge gap between both worlds in this respect. At a higher structural level, connections can be envisaged between silicon devices and arrays of neural tissues. In the future, the availability of such integrated neuroelectronic systems will help to unravel the nature of information processing in neuronal networks and will enable new physical–biological computational algorithms.

Novel architectures for novel computing technologies: Nanoelectronics will produce the billion transistor chips needed for ever more complex ambient intelligent systems. However, it is not at all clear that nanodevice-based circuits will be developed in the same way as the current computer architectures, since the latter do not necessarily provide superior computing capacity for many traditional applications / algorithms. Rather, the unique characteristics of nanoelectronics may enable radically different computational models, but these models must ultimately be incorporated into mainstream computing. These models must be able to deal with an exponential growth in requirements for data acquisition, processing, retrieving and storage.

Digital data capture: Digital data capture is a typical application where fundamental advances will be required in the nanoscale-terabit domain. Current digital imaging devices capture data with image sensors and use dedicated circuits and algorithms to process, compress and store them. A major line of development is to move to highly integrated systems that can handle fast signal acquisition and processing on the same chip. Coping with these very dense information streams requires embedded real-time content-based algorithms to extract and process large collections of data from the streaming digital signals. Other examples of strongly growing requirements in digital data handling and storage include body motion simulations based on motion capture technologies, and advanced data retrieving schemes needed for such large-scale projects as the Human Digital Memory or for the various "digital capture of cultural heritage" projects.

Long term digital data storage: IT departments increasingly need to retain digital documents indefinitely for legal, administrative or historical purposes, raising questions on how to preserve electronic information for many decades to come. Some of the issues are: estimating the lifespan of storage materials, dealing with the potential obsolescence of file formats, insuring backwards compatibility with applications and operating systems, and others. Solutions require simultaneous breakthroughs in data formatting software and in hardware issues s.a. long term storage media and readout systems. This requirement is further fueled by the upswing of medical digital records and associated medical imaging techniques which will become widespread in the era of predictive, preventive and personalized medicine.

Display technology: Display technology is another hardware area that has witnessed rapid evolution over the recent years. Future applications will put increasing demands on resolution, flexibility, wearability, true 3-D rendition, and system intelligence. Meeting these challenges will require disruptive solutions for display materials, interface devices, and visual system software technologies.

Self-Repairing and Self-Evolving Computational Devices: The research efforts in this area only scratched the surface of this problem, which will become increasingly more important as transistors shrink and computational devices are embedded in everyday objects or sent to outer space or inaccessible areas of this planet, not to speak within the human body. The ability to self-protect, self-heal, and self-adapt of living organisms is not achieved by any computational device. Our bodies have been completely renewed over the years and yet they maintain self-consistency and even better operation in most cases. The design of novel fault-resistant and self-evolving computational devices needs a concerted research effort in materials, electronics, hardware architectures, software architectures, and theoretical computer science. The European research landscape has a critical mass to address these issues and will certainly benefit from a program that encourages renewed interdisciplinary work.

4.4 The Team Player: Future Problem Solving Technologies

We are now facing another "Software Crisis" that far outstrips the crisis of the late 1960s and 1970s. This new crisis has arisen for similar reasons to the earlier one: device technologies have developed at an intrepid rate and the complexity of systems has grown dramatically but software technologies have failed to keep pace. Europe has traditionally had a strong reputation for the quality of its software, particularly in the areas of embedded systems and other high integrity systems. This flagship addresses the challenges by embarking on a search for new problem solving, and problem posing, technologies that will address the technical challenges of multi-core and the inevitable march towards exa-scale computing over the coming decade. The expectation is that the solutions will have to be technology agnostic. To address the challenges we will have to mobilise interdisciplinary teams involving theoreticians, software engineers, psychologists and social scientists.

While progress has been made in solving problems with computers, there is little work in *posing the problem* in automated fashion. The ambition is to automate posing and solving problems in multiple, unstructured domains ranging from the modelling of highly complex systems (such as considered in e-science) by way of use in an industrial context (such as automation) to day-to-day applications. Humans should be enabled to interact with the computer in a human way via multi-modal interfaces.

This calls for completely new programming paradigms, program development processes and programming tool chains, approaches to ensure reliability, maintainability, repairability and trust. The software systems will become so complex that we will have to borrow from the models of self-organisation in nature – but make them transferable and usable in real-world technology. The two main challenges are: the problem posing challenge; and the programming massive ICT challenge.

Problem Posing Challenge: The idea of posing problems to computers directly, let them "program themselves" and then have them compute the solution is only now coming into reach. The tools needed for approaching this challenge are numerous, including machine-interpretable representations of first principles, real-world concepts and ontologies, formalisms for describing problem domains, etc. These tools will all have to be combined into a framework enabling the interaction with humans, distributing the problem formulation tasks onto the network, analysing the results and then distribute it to (another) network to compute the solution – finally processing the answer so that it becomes human understandable. There is also another, just as exciting application area: today's computers solve problems we pose to them – we humans become a bottleneck. It would be much more effective, if computers recognised problems to be solved from their observation of nature and the environment directly. This is a system automation problem, with sensory inputs and actuator outputs to the environment, monitoring it and determining that a new problem may arise, expressing/transforming it into a solvable formulation, solving it and acting back on environment with the solution.

Programming massive ICT Challenge: Hardware manufacturers are committed to roadmaps to produce exaflop machines by 2020. The programming languages and compiler technology that will allow general HPC users to effectively harness and exploit this power are yet to be developed. This can be considered a challenge that is much greater than the development of the first programming languages, which started fifty years ago and is still going on. Moreover, the emerging data centre technology (which forms a basis for "cloud computing") will need programming technologies that also take into account the energy consumption of the programs run on them.

There are a number of "enabling" challenges which must also be addressed in order to realise these ambitious goals. A number of these are in areas where Europe is already pre-eminent and incorporating effort in these areas into this FET-F will ensure that we maintain our competitive lead:

Modelling and formal methods Challenge: Massive computers pose new challenges to modelling and formal methods – not only will the new programming languages bring new challenges to these communities, but, as computers become ever more pervasive, new application domains will also present new challenges. For example, embedded systems increasingly bring the digital world into contact with the analogue; this calls for a new theory of computing that integrates continuous and discrete mathematics in a fundamentally new way. In this context, harnessing the metaphor of "self-repair" by casting it in the framework of programming languages is another new challenge.

Future communication technologies and services Challenge: In the near future, secure communication channels of unlimited bandwidth, processing power and storage capacity will be available to everyone at very low cost. The challenge will be how to turn the potential of these technologies into reliable services, i.e., how can new services be designed and offered in such a way that they find acceptance?

Heterogeneous Cyber-Physical Systems and social ICT Challenge: Systems that are both connected to the Internet and (at the same time) controlling processes in the real world (cyber-physical systems) will become more and more widespread. These systems will form clusters (e.g., a fleet of cars that communicate with each other and afford some kind of "swarm intelligence") of highly diverse subsystems. Such highly heterogeneous "organisms" must become programmable as if they were a single system. At the same time, this area is particularly dependent of ICT becoming "social" in the sense that it really serves its users in society – which means that methods of ensuring trust must be developed for this system class, along with new usability concepts.

Programming ICT for combined energy/communication networks Challenge: In the near future, e-Energy technologies, in particular interweaved energy-packet switching power grids combined with communication networks and decentralised computing nodes will be implemented for much more efficient energy distribution. Such systems are highly heterogeneous, distributed over long distances and affected by all kinds of disturbances. The unified programming of such large-scale real-time systems that have to work highly reliable in the most adverse conditions is a huge challenge for programming technologies.

Trust, Reliability and Security Challenge: Mobile and pervasive computing environments pose new challenges in this area: trust models that are both spatially and temporally aware must be developed. The abilities to detect anomalous events, to plan and to execute appropriate responses are major challenges in the security domain. The use of more rigorous methods in software certification must become the norm rather than the exception.

Data deluge Challenge: Just as exaflop computing poses challenges to the programming paradigms, data repositories containing exabytes of data will present huge challenges. It is likely that we will need to develop totally new approaches to searching and other basic processing functions. Such a deluge of data is only useful if we can develop automated techniques to extract knowledge and wisdom from the raw data.

4.5 Robot Companions for Citizens

Over the last five decades, the development of robot technology has been dramatic in terms of accuracy, speed, dexterity, pricing, and application areas. Today, robots assemble all kinds of goods at high speed, explore Mars, perform surgery and are just about to relieve us from many of our household chores. These capabilities could be exploited in order to address and provide usable and acceptable solutions to many critical societal problems, such as health and ageing, environmental monitoring, safety and security. However, the more successful robotics becomes, the more the gap widens between what film and book writers, as well as the general public, expect from future robot systems – and what robot technology can actually deliver. Today's robots do not have the desirable properties of living systems, such as behavioral and energetic autonomy, evolution, growth, adaptation, self-repair, bio-compatible and resilient morphologies, adaptive perception and communication. These limitations greatly restrict the usefulness of robotics for helping people, interacting and merging with them, or substituting for them in dangerous missions.

In this FET-F, a bold approach will be pursued at laying the foundation for the Robot Companions for Citizens, i.e., types of artifacts that finally live up to the promise of being machines that can become *truly autonomous, adaptive,* and more *helpful to humans* throughout their lifetime in the most unobtrusive way.

The robot companions will come in many flavours, depending on the main function they are to perform: they can operate alone or in groups, they can be fixed to one location, mobile or applied to the human body, they could be sent to outer space or injected into our bodies. Robot companions will not necessarily be made only of mechatronic components nor will they necessarily be a humanoid. To achieve autonomy, adaptivity, and self-repair, they will take on shapes and employ technologies that are best suited for their intended function.

With the new generation of "Self-X" artifacts, it will no longer be necessary to replace human-assistive devices – ever! Even more, the human will get to know the device (and vice versa) so well that its replacement will actually be very difficult. Robot companions will understand a human's physiological and emotional state and will adapt their operation accordingly. They will continuously communicate with other personal devices and other Robot companions across the planet to self-evolve into novel functions and may, as a consequence, try novel behaviors or suggest to the human owner ways in which they could be upgraded when new modules are necessary.

These artifacts will be extremely complex, but at the same time they must be extremely reliable. Fatal system errors and complete breakdowns will not be acceptable for Robot companions – they will have to provide their services and functions reliably and at all times. To achieve such "perfect and flawless" behaviour, completely new design principles and technologies for robotic and computing elements must be developed. They must be capable of self-healing, self-adaptation, self-organisation and self-evolution ("Self-X"). Such robot companions will adapt and reconfigure themselves to support our changing needs – we humans will no longer be forced to adapt to our machines!

Clearly, this research will have to integrate virtually all previous research in robotics, artificial intelligence and cognitive/life sciences – such as morphologies and materials, sensors and actuation technologies, perception and cognition, multi-modal human-machine interfacing, control and embedded systems, distributed real-time systems, dependability, self-repair, evolvability, adaptation, and many more.

In order to set the foundations for robot companion research and development, several challenges will have to be met, including:

Robot "brains": Develop systems that are capable of integrating rich and multi-modal perception, of solving more than a single task, of finding solutions to problems without being instructed, of adapting to changing environmental and task requirements, of understanding and of communicating with humans and with their peers. Robot brains will not necessarily mimic human brains and may not necessarily be inspired from neuronal technologies as long as they achieve those properties desired.

Robot "bodies": Develop technologies that allow robot companions to grow their body and to adapt their physical shape to a certain task (class). This calls for materials, structures and actuators that go beyond the rigid plastic and metal structures of today's robots in that they will be adaptive, compliant, safe for humans, self-repairing and self-morphing, and bio-compatible. We must develop novel sensor technologies that are capable of providing richness, dynamic range, and multi-modal properties of animal perception. To achieve true adaptation to a certain "task niche", the living robot will have to adapt its body in combination with the evolution of its "mind". It is necessary to develop electronic architectures that can support the requirements for adaptation, distribution, and rich sensory perception, yet at the same time, be compatible with novel body structures.

Robot energy supplies and "metabolisms": Today's robot systems are severely limited by the dependence on electrical energy storage and/or the presence of sunlight for their energy supply. An alternative could be to break away from the classical electrical energy cycle and create new cycles with "metabolic" energy converters and/or actuators that can be driven directly without going through the electrical cycle – all modeled on energy conversion and actuation principles found in animals.

Miniaturization and Distribution: Develop robots that can be small, bio-compatible and possibly bio-degradable to safely live within human bodies in order to carry out monitoring, drug delivery, and repair. Micro- and nano-robots may exist in large numbers and should be able to coordinate and perform dynamic division of labor according to the task requirements and ever-changing environmental conditions. Distributed micro-robots may operate coherently over large spatial extension in an asynchronous manner, may be connected to the internet or other wireless networks, and may have distributed sensing and actuation capabilities.

Human-robot interaction: Living robots designed to operate with humans must also be able to learn from a human partner like a child – as it grows and physically adapts to its tasks. This is a completely new and unchartered field in the context of robotics, but it is a precondition for the ultimate robot to become an accepted "peer" for humans. Major challenges reside in enhanced perception, communication, and rich and safe physical interaction. Furthermore, strong attention should be given to address societal implications and industrial opportunities. In particular, the role of common regulations in Europe (on the practical use of autonomous robots in public and private environments, responsibility, insurance), and actions to promote the growth of a new European robotics industry (for example, pre-commercial public procurements) should be considered specifically. It will also be necessary to carry out extensive studies of human expectations and reactions to these novel forms of robotics, as well as significant research in the ethics of robotics as these machines become more autonomous and "closer" to humans.

Roboethics. The development of robot companions as truly autonomous entities will give rise to completely new ethics – how can machines that are so close to humans be designed and used for the advancement of society and how can we prevent its misuse against humans or humankind? This research will have to involve a re-consideration and possibly a re-definition of human-centred concepts like autonomy, consciousness, free will and decision making, emotions taking into account that these concepts do not necessarily reflect the same reality and semantic meaning.

Above all, the integration of all these technologies, methodologies and concrete modules is a challenge in itself that requires careful investigation. Therefore, one can see very strong links between this FET-F and other FET-Fs. These are as follows:

(i) **Understanding life:** Exploitation of insight into ontogenetic and phylogenetic development for the growth processes of the robot's brains and bodies as well as its skill development.

(ii) **Programming Technologies:** These machines will not only become the most complex systems ever built, but also the biggest challenge in terms of programming real-time sensor-actuator networks, interpreting high volume complex multimedia data flows, ascertaining "safe" behaviour of the system with formal methods, etc.

(iii) **Massive ICT:** Clearly, for implementing brains, nervous systems, and decentralised actuator control, most of the new massive ICT technologies can be directly implemented in the ultimate robot – some of them will even be essential.

5 Recommendations

FET flagship initiatives will change the way research and innovation are managed in Europe. A mandatory requirement is to gather and focus all the efforts towards the realization of a limited number of such flagships. All the stakeholders should be part of the consultation process.

The following set of actions is suggested in order to develop the FET flagship description, to analyze according to the criteria and to prepare the programme.

Recommendation 1:

A series of workshops and consultations should be organized, aimed at focusing the challenges, further elaborating and evaluating each candidate FET-F according to the criteria outlined in section 3. The workshops should gather experts of the different fields and communities involved into the FET-F, including social sciences. It is required to produce a complete description of each candidate FET-F and a detailed SWOT analysis.

Recommendation 2:

The findings from the consultation workshops should be discussed in relevant advisory committees and with experts from industry. Member states and national research funding agencies should also be involved early in the process.

As was already recommended in a previous ISTAG report, the FET budget should be substantially increased. Moreover a specific budget should be allocated in order to fund the FET-flagship programme.

Recommendation 3:

The FET flagship initiatives should be considered complementary to the existing FET programme. A specific budget should be allocated to fund the FET-flagship programme.

6 Conclusion

This report has introduced and motivated the definition of FET flagships (FET-F) that address challenges in research and innovation requiring radical transformations of ICT for 2020 and beyond. A deep and detailed analysis of the FET-F concept has been performed resulting in a precise definition. Motivations for such FET flagship initiatives have also been analysed and a set of eight criteria have been selected in order to assess the relevance of the choice. Finally five topics for candidate FET flagships have been proposed and described. They encompass many scientific challenges and address crucial societal needs. However, there may still be some gaps (education for example is not directly addressed).

Hence a more complete study has to be done on all the aspects of theses FET-F. More expertise is needed, SWOT analysis has to be performed and a plan of actions has to be set up. However, the FET working group of the ISTAG is deeply convinced that this is a very promising avenue for developing FET flagships, leveraging on the successes of European research, transforming them into radically new technologies and creating new markets for answering crucial societal needs.

Annex I – Members of the ISTAG Working Group on FET FLAGSHIPS

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European Commission

Luxembourg: Publications Office of the European Union

2009 — 40 pp. — 210 x 29,7 cm

ISBN 978-92-79-13879-9

doi 10.2759/23475

European Challenges and Flagships 2020 and beyond

KK-80-09-966-EN-C

Report of the ICT Advisory Group (ISTAG)

July 2009

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Printed by OIB

SEVENTH FRAMEWORK PROGRAMME

doi 10.2759/23475

ISBN 978-92-79-13879-9

9 789279 138799

European Commission
Information Society and Media